

Express Mail Label No.: EL751290694US

PATENT APPLICATION  
Docket No.: 2807.2.22.6

**UNITED STATES PATENT APPLICATION**

of

**Michael H. Myers**

**John N. Hait**

**and**

**Steven F. McDaniel**

for

**PHOTONIC WAVELENGTH ERROR DETECTOR**

## BACKGROUND

### 1. The Field of the Invention

This invention relates to computer systems, telecommunication networks, and switches therefor and, more particularly, to novel systems and methods for switching and processing photonic information.

### 2. Background Discussion

Multiplexing is a method for transmitting multiple, distinct signals over a single physical carrier medium. Much of the protocol of computer hardware deals with the encoding and decoding of signals according to some time scheme for maintaining signal integrity and uniqueness from other signals. In conventional time-division types of multiplexing, signals are transmitted within specific time slots or burst positions. In order to prevent individual bits from being transmitted at the same time, each burst of bits may be encoded into a signal and transmitted over the carrier medium at a specific time.

As transmission rates increase, the individual time divisions available for each small quantity of information in a signal are reduced. However, with the advent of photonic processing, the transmission, encoding, and decoding of photonic signals taken from the electromagnetic spectrum, deserve further consideration. In conventional computer systems, as well as conventional telecommunications networks, the switching, routing, and transmission of signals throughout networks and between processors or processes may be a major limiting factor in performance. Typically, transmissions of a signal require encoding of the signal in a carrier medium, according to a protocol or format.

Thereafter, transmission occurs as a physical phenomenon in which light, or other electromagnetic radiation, electrical signals, mechanical transmissions, or the like are transferred between a source and a destination. At the destination, a decoder must then manipulate the physical response to the incoming signals, thus reconstructing original data encoded by the sender. Communications in general may include communications between individual machines. Machines may be network-aware, hardware of any variety, individual computers, individual components within computers, and the like.

Thus, the issue of sending and receiving information or message traffic is of major consequence in virtually all aspects of industrial and commercial equipment and devices in the information age. Whether communications involve sending and receiving information between machines, or telecommunications of data signals, audio signals, voice, or the like over conventional telecommunications networks, the sending and receiving requirements of rapidly encoding and decoding are present.

With the advent of photonic signals and photonic signal processing, new speed limits are being approached by transmission media. Moreover, origination of signals can now be executed literally at light speeds. Accordingly, what is needed is a system for multiplexing photonic signals over photonic carrier media in such a way as to maximize speed, while maintaining the integrity of information.

To be most useful, communications and switching equipment must interface with data channels from a plethora of sources. An ability to transmit and redirect multiple channels simultaneously and independently, increases the capacity and usefulness of transmission, multiplexing and switching equipment. Over the years several standard methods have been

developed for packing multiple channels onto a single transmission medium. In optical frequency division multiplexing (OFDM) and wavelength division multiplexing (WDM), each channel has a unique wavelength which typically remains constant with time. In spread spectrum systems, all channels may have substantially the same average wavelength with short term variations that are unique to each channel. Typically, sets of orthogonal functions are used to define channel wavelengths. In most systems and applications, it may be desirable that the wavelength of each channel can be described as a function of time, distinct and unique from all other channels. An ability to wavelength shift photonic signals from one channel, whose wavelength can be defined as a function of time, into any other channel would facilitate the transmission, multiplexing and switching of an extremely wide range of photonic signals.

One dilemma in engineering photonic systems is the conversion of signals or information between the electronic and photonic domains. Photonic systems are capable of high transmission rates and distances. Computers and control equipment are typically electronic due to their flexibility, low cost and wide availability. Typically, switching and multiplexing require the conversion of optical signals into electrical signals for processing and control, followed by reconversion into the optical domain for further transmission. An ability to direct and control a photonic stream of data with electronic devices and systems without requiring conversion of the photonic data stream to the electronic domain would leverage the best characteristics of each domain.

While it may be desirable to leave data in the photonic domain when transmitting, multiplexing and switching photonic signals, it is often desirable to encode an electronic data signal onto an existing carrier without additional complexity and cost. An ability to process

photonic or electronic data signals with the same mechanism would simplify interfacing with a wide range of communications, process control, and computational equipment.

One difficulty in interfacing a wide variety of photonic equipment is the assignment of channel wavelengths and encoding techniques. Setup and configuration become problematic. An ability to automatically channelize (change the wavelength of a photonic carrier to a given channel) and transparently pass along a data encoded photonic stream across a network of photonic equipment without prior knowledge of the channel wavelengths and encoding techniques would reduce the cost and complexity of deploying photonic equipment.

Another issue in photonic transmission systems is carrier wavelength variability due to component variability, temperature drift, system jitter and other factors. Carrier wavelength variability makes it difficult to densely pack channels onto a transmission medium without collisions occurring, especially when multiplexing channels from multiple sources. Typically, expensive, temperature-compensated, reference lasers or light sources are required to stabilize a photonic signal. Most state-of-the-art photonic transmission systems require conversion to the electronic domain followed by remodulation of a light source and retransmission in order to eliminate any jitter introduced during transmission. An ability to compensate for wavelength variability of existing photonic streams without remodulation and retransmission would increase the capacity and lower the cost of transmission, multiplexing and switching equipment.

#### BRIEF SUMMARY AND OBJECTS OF THE INVENTION

In view of the foregoing, it is a primary objective of the present invention to provide a method and apparatus for transmitting, multiplexing and switching photonic signals without

requiring conversion to the electronic domain. It is also a primary objective of the present invention to provide a method and apparatus for embedding electronic data signals onto existing photonic carriers and signals.

One objective of the invention is to provide a system that facilitates the transmission, multiplexing and switching of an extremely wide range of photonic signals. It is also an objective of the invention to provide a system for multiplexing photonic signals over photonic carrier media in such a way as to maximize speed, while maintaining the integrity of information. Another objective of the invention is the ability to interface with data channels from a plethora of sources, to transmit and redirect those data channels simultaneously and independently. In particular it is desired to wavelength shift photonic signals from one channel, whose wavelength can be defined as a function of time, into any other channel without requiring conversion to and reconversion from the electronic domain. It is also an objective of the invention to automatically channelize and transparently pass along a data encoded photonic stream across a network of photonic equipment without prior knowledge of the channel wavelengths or encoding methods and to compensate for wavelength variability of existing photonic streams without retransmission.

The present invention uses various embodiments to wavelength shift photonic signals. Wavelength shifting is also applied as a mechanism to multiplex, switching and transmit photonic signals. In certain embodiments in accordance with the invention, an apparatus for wavelength shifting uses modulation techniques to change photonic carrier wavelengths. Modulation techniques may be selected to be appropriate to a modulation device of choice. A

particular modulation device may be driven by a modulation synthesizer producing a controlling waveform optimized for the device.

Consistent with the foregoing objectives, and in accordance with the invention as embodied and broadly described herein, an apparatus and method are disclosed, in suitable detail to enable one of ordinary skill in the art to make and use the invention.

### BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objectives and features of the present invention will become more fully apparent from the following description and appended claims, taken in conjunction with the accompanying drawings. Understanding that these drawings depict only typical embodiments of the invention and are, therefore, not to be considered limiting of its scope, the invention will be described with additional specificity and detail through use of the accompanying drawings in which:

Figure 1 is a schematic block diagram of a wavelength shifting apparatus in accordance with the invention;

Figure 2 is a schematic diagram of a quadrature Mach-Zehnder modulation device used in accordance with the invention;

Figure 3 is a graph of the Mach-Zehnder device transfer function in accordance with the device of Figure 2;

Figure 4 is a schematic block diagram of a modulation synthesizer used in accordance with the invention;

Figure 5 is a schematic block diagram of an embodiment of a modulation synthesizer configured to perform ON/OFF keying in accordance with the invention;

Figure 6 is a schematic diagram of a phase modulation device used in accordance with the invention;

5 Figure 7 is a schematic block diagram of an embodiment of a modulation synthesizer configured to perform frequency shift keying in accordance with the invention;

Figure 8 is a schematic block diagram of a wavelength error detector in accordance with the invention;

Figure 9 is a schematic block diagram of a tunable wavelength error detector in accordance with the invention;

10 Figure 10 is a schematic block diagram of a tunable wavelength error detector in accordance with the invention; and

Figure 11 is a schematic block diagram of a channel allocation mechanism in accordance with the invention;

15 Figure 12 is a schematic block diagram of a tunable wavelength stabilized transmitter in accordance with the invention;

Figure 13 is a schematic block diagram of a recursive wavelength shifter in accordance with the invention; and

20 Figure 14 is a set of frequency domain graphs of several signals associated with one embodiment of the recursive wavelength shifter depicted in Figure 13.



## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

It will be readily understood that the components of the present invention, as generally described and illustrated in the Figures herein, may be arranged and designed in a wide variety of different configurations. Thus, the following more detailed description of the embodiments of the system and method of the present invention, as represented in Figures 1 through 14, is not intended to limit the scope of the invention. The scope of the invention is as broad as claimed herein. The illustrations are merely representative of certain, presently preferred embodiments of the invention. Those presently preferred embodiments of the invention will be best understood by reference to the drawings, wherein like parts are designated by like numerals throughout.

Those of ordinary skill in the art will, of course, appreciate that various modifications to the details of the Figures may easily be made without departing from the essential characteristics of the invention. Thus, the following description of the Figures is intended only by way of example, and simply illustrates certain example embodiments consistent with the invention as claimed.

The design, implementation and deployment of photonic systems involves the convergence of a number of disciplines each with their own working vocabularies. Additionally, the novelty of the present invention presents some new terms and concepts. The following definitions therefore are provided for the readers convenience:

Channel: A virtual medium for signal propagation. Channels allow a single medium to carry multiple signals simultaneously.

Channel Spacing: The distance between channels usually expressed in cycles per second.

Wavelength Shifting: The act of changing the wavelength of a photonic signal, particularly the carrier.

Wavelength Variability: A measure of wavelength deviation from an ideal or desired wavelength over a given period of time.

5 Wavelength Stabilization: The act of reducing wavelength variability.

Wavelength Pattern: The pattern (over time) followed by the wavelength of a photonic signal, particularly the carrier. May be a constant. The present invention associates wavelength patterns with channels.

Channelization: The act of shifting the wavelength of a photonic signal to match the wavelength pattern of a given channel.

Wavelength Signature: An information set that captures the essential elements of the wavelength of a photonic signal such as the pattern, signal jitter, variance etc.

Orthogonal Signals: Signals that do not correlate over a given period of time. Selecting wavelength patterns that are orthogonal helps minimize interference between channels.

15 Wavelength Division Multiplexing: Combining multiple signals onto a medium where each signal has a different wavelength.

Spread Spectrum Channels: Channels with wavelength patterns that are very dynamic. Usually based on orthogonal functions.

20 Spreading Function: Essentially a wavelength pattern used to change fixed wavelength channels to spread spectrum channels.

Gathering Function: Essentially a wavelength pattern used to change spread spectrum channels to fixed wavelength channels.

Modulation: The act of varying a frequency, amplitude, phase or similar characteristic of a signal.

Modulation Waveform: A waveform used to modulate a signal and thereby vary the frequency, amplitude, phase or similar characteristic of a signal. The present invention uses a modulation waveform to drive (i.e. control) a modulation device.

Modulation Synthesizer: A method or apparatus that generates a modulation waveform in response to various control parameters or signals.

Pre-modulation: Modulation of the modulation waveform. The modulation synthesizer of the present invention uses pre-modulation to encode data simultaneous with wavelength shifting.

In optical and photonic systems it is usually more convenient to refer to carriers in terms of wavelength rather than frequency. Despite this preference, channel spacing is usually expressed in frequency units rather than units of length. Throughout this description it is implied that the amount of shifting is expressed in terms of frequency (Hz) while the result (a change in carrier wavelength) is referred to as wavelength shifting.

Referring to Figure 1 specifically, while generally referring to all the Figures, a wavelength shifter 10 with stabilization and data encoding may include a modulation synthesizer 12, a wavelength error detector 14, and a modulation device 16. The modulation device 16 may receive a photonic signal 18 and provide a channelized photonic signal 20 wherein the wavelength follows a signature or pattern associated with a channel.

The modulation device 16 may receive a photonic signal 18 that may be composite or non-composite. Composite signals may contain a plurality of wavelengths, each wavelength

definable as a function of time, while non-composite signals have a single wavelength also definable as a function of time. Regardless of the complexity of the photonic signal 18, the modulation device 16 receives the photonic signal 18 and may provide a channelized photonic signal 20 wherein each wavelength follows a pattern corresponding to a particular channel.

5 In most embodiments, the modulation device 16 may be a full-duplex device capable of simultaneously modulating signals from both directions. With a full-duplex modulation device 16, the wavelength shifter 10 may be also full-duplex. In full-duplex operation the modulation device 16 receives the photonic signal 18 and provides the channelized photonic signals 20 in each direction. For simplicity, this description is restricted to half-duplex operation unless otherwise noted.

10 Under proper control, the wavelength shifter 10 may direct a non-composite photonic input into any one of an arbitrary number of output channels. Composite signals may be similarly directed. For example, a composite signal comprised of multiple wavelengths that are equally spaced by a fixed frequency interval, may be shifted up or down as a group by an arbitrary frequency to occupy a new set of wavelengths. The wavelength shifter 10 may be designed to stabilize and channelize the photonic signal 18. Typically, the channelized photonic signal 20 will have the same complexity as the photonic signal 18 and will be a composite signal if the photonic signal 18 is a composite signal. The channelized photonic signal 20 differs from the photonic signal 18 in that the wavelengths of the photonic signal 18 may be shifted to match a wavelength pattern associated with a channel. In some embodiments, the photonic signal 18 may also have a wavelength pattern but it is generally assumed that the wavelength patterns are externally originated and may be unknown to the system of interest.

The modulation synthesizer 12 may receive an optional data signal 22 and a shift signal 24. The modulation synthesizer may provide a modulation waveform 26 designed to channelize the photonic signal 18 via the modulation device 16. The optional data signal 22 may be used to pre-modulate the modulation waveform 26 and effectively encode data in the channelized photonic signal 20. Pre-modulation allows data encoding techniques such as Frequency Shift Keying, ON/OFF keying, and code division keying to be performed by the wavelength shifting modulation device.

Time-domain orthogonal codes may be directly used by the modulation synthesizer 12 when pre-modulating the modulation waveform. Frequency-domain orthogonal codes such as frequency shift keying Walsh codes may be converted to a time-domain waveform and used to pre-modulate the modulation waveform. Joint time-frequency codes may also be used. For example, one bits may be encoded by a positive frequency shift in an alternating ON-OFF pattern while zero bits may be encoded by a negative frequency shift in an alternating OFF-ON pattern.

The ability to simultaneously encode data, channelize and stabilize a photonic signal via a single modulation device has not been found in the art and appears to be unique to the wavelength shifter 10. In some embodiments, the optional data signal 22 is not used and the modulation synthesizer 12 may simply be a voltage-controlled quadrature oscillator.

The wavelength error detector 14 may monitor the channelized photonic signal 20 and provide a wavelength error signal 21 useful for correcting errors in wavelength. The wavelength error detector 14 may monitor a single channel or a representative channel of a group of active channels. While certain embodiments cannot independently shift and correct wavelength errors in separate channels (using a single wavelength shifter 10), wavelength errors may be minimized

across multiple active channels (using a single wavelength shifter 10) by generating a wavelength error signal that is the weighted average of the wavelength error of each channel. Typically, if a group of channels is derived from the same laser or light source, selecting a representative channel may be just as effective and much less costly than generating an averaged wavelength error signal.

The wavelength shifter 10 allows stabilization of a single channel or group of channels without requiring direct control of a laser or light source. Separating stabilization from the actual laser device allows for greater flexibility in designing and deploying photonic systems.

Separating the wavelength error detector 14 from the synthesis and modulation functions of the wavelength shifter 10 also allows for system design flexibility. Depending on the application, the wavelength error detector 14 may operate about a wavelength that is fixed or tunable. The wavelength error detector 14 may be dedicated to a single wavelength shifter or shared among multiple wavelength shifters 10. The wavelength error detector 14 may also be dynamic and support wavelength signatures or patterns. Regardless of the application, the wavelength error signal 21 provides feedback to the modulation synthesizer 12 which may effect shifting, stabilization and channelization of the photonic signal 18.

Certain embodiments in accordance with the present invention use a modulation device to shift and stabilize the wavelength of a carrier. Data encoding may also be performed with the wavelength shifter 10 via an optional data signal 22. A shift signal 24 controls the extent by which a wavelength may be shifted by the wavelength shifter 10 (neglecting any wavelength error correction). The shift signal 24 may have a constant value or the shift signal 24 may be a dynamic signal with a spreading or gathering function.

Separating the shift signal 24 from the wavelength error signal 21 allows for greater control and flexibility of the wavelength shifter 10. Wavelength shifting of the photonic signal 18 may advantageously occur through either mechanism. For example, the shift signal 24 may correspond to a wavelength pattern, while the wavelength error signal 21 may provide fine tuning of the average wavelength of the channelized photonic signal 20. In the embodiments depicted in Figures 1-11, the shift signal 24 and the wavelength error signal 21 are equal and independent in their ability to effect a wavelength shift on the photonic signal 18 and thereby provide the channelized photonic signal 20.

The wavelength shifter 10 may be used to interface between systems with dissimilar channel wavelength patterns. For example, one system may use spread spectrum channels while another may use channels with fixed wavelengths. By providing a spreading function or conversely an unspreading function to the shift signal 24, the wavelength shifter 10 may be used to convert fixed wavelength channels to spread spectrum channels and vice versa. Conversion between two spread spectrum channels may occur by providing the difference of two spreading functions to the shift signal 24.

In certain embodiments, the shift signal 24 controls the amount of shift in units of frequency (Hz). In some embodiments, the shift signal 24 provides a shift range, allowing wavelength error correction to occur within that range. Specifying a shift range on the shift signal 24, allows the wavelength shifter 10 to lock onto a particular channel when wavelength shifting a composite photonic signal. Wavelength shifting a composite photonic signal without a shift range may result in channel wandering should a composite signal experience fading or some other kind of degradation.

The shift signal 24 may be data keyed instead of using the optional data signal 22. Data keying with the shift signal 24 effectively creates spread spectrum or frequency domain data keying. Frequency shift keying is perhaps the simplest form of frequency domain data keying wherein the shift signal 24 alternates between two shift values to encode the data. The shift signal 24 may be data keyed with binary codes such as Walsh codes. Continuous codes may also be used.

One operation, that may be used for processing signals and creating filters, is a delay and sum operation. By controlling the relative phase of summed signals various degrees of constructive and destructive interference may be accomplished at a particular wavelength or frequency. By splitting photonic waves into multiple paths of various delays and recombining the split waves onto a single path, filters of various types can be created.

One element used in accordance with the invention is a phase modulator. Phase modulators often vary the index of refraction of a particular section of a waveguide and may be controlled with an applied voltage. Changing the index of refraction effectively changes the propagation time or delay through a medium. The ability to dynamically control the delay of a path via an applied voltage adds additional power for processing photonic signals.

For example, a Mach-Zehnder modulator may split a photonic signal onto two complementary pathways of identical length each with a phase modulator. With no applied voltage, the split photonic signals arrive in phase and effectively sum to the original photonic signal. Symmetrically increasing the delay of one path and decreasing the delay of the other path (via the applied voltages) allows the amplitude of the combined photonic signal to be modulated.



At a certain point the combined signals will be 180 degrees out of phase resulting in a zero amplitude signal known as a dark point.

Normally, amplitude modulation produces dual side bands resulting in wasted bandwidth. Quadrature modulation involves using two modulators that operate 90 degrees out of phase. Each modulator produces dual sidebands. Two of the sidebands cancel while two of the sidebands sum to create a single sideband.

Various modulation devices may be suitable for the modulation device 16. Suitable devices may include a quadrature Mach-Zehnder modulation device 16a, a phase modulation device 16b and a single Mach-Zehnder modulation device in concert with a phase modulator. Other possibilities include a single Mach-Zehnder modulation device followed by a filter, or a photonically driven device such as a stimulated Brillouin scatterer, a stimulated Raman scatterer, or a four-wave mixer. In certain embodiments, component cost can be reduced by selecting the modulation device 16 optimized for shifting within a specific frequency range.

Referring to Figure 2, the modulation device used in certain embodiments may be the quadrature Mach-Zehnder modulation device 16a. A quadrature device facilitates wavelength shifting by quadrature or single sideband modulation. The quadrature Mach-Zehnder modulation device 16a may have an upper branch 28 and a lower branch 30. The upper branch 28 and the lower branch 30 may be complementary Mach-Zehnder modulators that perform in a quadrature mode when driven by a modulation waveform 26.

With a quadrature modulation device, the modulation waveform 26 may have a quadrature waveform component 26a and a quadrature waveform component 26b. Waste light

31 may be emitted at a branch junction 32. In some embodiments it may be desirable to use the waste light from the branch junction 32 to perform phase stabilization or other useful functions.

Referring to Figure 3, a transfer function 34 typical of the upper branch 28 and the lower branch 30 may be a function of the voltage of the modulation waveform 26. The transfer function 34 may correspond to a cosine wave. In certain embodiments, the modulation synthesizer 12 may provide a waveform optimized to for a particular modulation device 16. Proper biasing of the upper branch 28 and the lower branch 30 modulation waveform voltages allow each branch to operate at a dark point 36. Operating at the dark point 36 may be advantageous to reduce transmitted power and signal distortion.

In certain embodiments, applying a ramp function beginning at the dark point 36 produces a sine wave of negative polarity. Therefore, small fluctuations in quadrature waveform components 26a and 26b about the dark point 36, produce modulations that are substantially bipolar and linear. Small fluctuations in the quadrature waveform components 26a and 26b that are not biased to the dark point 36 may produce modulations that may be unipolar. Transmitted power may also be substantially increased. Larger amplitude fluctuations in the modulation waveform 26 may generate noise harmonics in the channelized photonic signal 20 due to the non-linearities in the upper branch 28 and the lower branch 30.

Noise harmonics in the channelized photonic signal 20 may be substantially eliminated by dividing the modulation waveform components 26a and 26b by the transfer function 34 of the upper branch 28 and the lower branch 30. Driving the depicted Mach-Zehnder quadrature modulation device 16a with waveform components 26a and 26b, that are triangular or sawtooth in shape (having maximum and minimum amplitudes corresponding to peaks and valleys in the

transfer function 34), substantially eliminates the introduction of noise harmonics in the channelized photonic signal 20.

The modulation synthesizer 12 may be embodied in a variety of forms including discrete circuitry, digital logic, software modules within a processor (with a digital-analog converter to drive the modulation device), and custom chips. Regardless of the implementation scheme selected, the modulation synthesizer 12 may be designed to drive the modulation device 16 as controlled by the error signal 21 and the shift signal 24. Implementation details may be quite specific to the modulation device used and other factors such as bandwidth, cost, and response time.

In particular, the method of data keying and the characteristics of the modulation device 16 may significantly affect the overall structure of the modulation synthesizer 12. With certain embodiments it may be beneficial to embed data keying within the shift signal 24 (external to the modulation synthesizer 12). Figures 4, 5 and 7 show three examples of a modulation synthesizer 12 that share certain common design elements with unique changes relevant to the respective method of data keying and the characteristics of the modulation device 16 used by each example.

Referring to Figure 4 specifically, while referring generally to all the Figures, the modulation synthesizer 12 may include an integration unit 38. The integration unit integrates and may optionally filter the error signal 21 to provide an integrated error signal 40. For example, low-pass filtering of the error signal 21 may be used to dampen the response of the wavelength shifter 10 and prevent overshooting a design point. A summing unit 42 may sum the shift signal 24 with the integrated error signal 40 and provide a total shift signal 44. In some

embodiments, the shift signal 24 may provide a lower shift 24a and an upper shift 24b to restrict the range of wavelength shifting. The summing unit 42 may be configured to confine the total shift signal 44 to the range specified by the lower shift 24a and the upper shift 24b.

Continuing to refer to Figure 4 specifically, while referring generally to all the Figures, the waveform generator 46 receives a total shift signal 44 and generates the modulation waveform 26 relevant to the modulation device 16. Quadrature versions of the modulation device 16 may require a quadrature waveform with waveform components that are substantially 90 degrees out of phase.

Referring to Figure 5, a quadrature version of the modulation synthesizer 12 may configure the waveform generator 46 to generate quadrature waveform components 26a and 26b that are shaped in a desired fashion, such as triangle waves. Figure 5 also shows that ON/OFF data keying may be added to the modulation synthesizer 12 by operably connecting the data signal 22 to an ON/OFF input 47 of the waveform generator 46. Data keying may be accomplished by selectively setting the quadrature waveform components 26a and 26b to a value corresponding to the dark point 36 of the upper branch 28 and the lower branch 30. For example, the upper branch 28 and the lower branch 30 may be operably set at the dark point 36 when the ON/OFF input 47 is in the OFF position.

Referring to Figure 6, the phase modulation device 16b may differ from the quadrature Mach-Zehnder device 16a. For example, quadrature or single sideband modulation may not be supported. Wavelength shifting may occur by applying an alternative waveshape, such as a ramp function, to the input. In the illustrated embodiment, the extent of wavelength shifting provided

by the phase modulation device 16b may be substantially proportional to the slope of the ramp function.

Sustaining a ramp function may be problematic with a finite modulation waveform 26 and the phase modulation device 16b. Several techniques may be used to ensure that finite limits are maintained on the modulation waveform 26. For example, frequency shift keying may encode ones with a positive frequency shift and zeros with a negative frequency shift. Circuit modifications may be added to substantially eliminate the DC terms of the data signal. Data encoding techniques may be applied to limit the one's density of the data stream to an acceptable range. Each of these techniques may limit the range of wavelength shifting attainable by the wavelength shifter 10.

Another solution involves driving the phase modulation device 16b with a sawtooth waveform 26c. The sawtooth waveform 26c may produce an opposite polarity wavelength spike 27 corresponding to vertical edges of the sawtooth waveform 26c. The duration of the opposite polarity wavelength spike 27 may be short enough to be irrelevant. The opposite polarity wavelength spike 27 may also cause a wavelength shift large enough to momentarily move the wavelength of the channelized photonic signal 20 outside the transmission range of the system of interest. The opposite polarity wavelength spike 27 may also be advantageously used to provide a clock signal and/or synchronize multiple data streams.

Referring to Figure 7, the modulation synthesizer 12 may be configured to support frequency shift keying. As compared to the embodiments of Figures 4 and 5, a multiplexer has been added and the shift signal expanded to a low shift 24a and a high shift 24b. In the depicted embodiment, the low shift 24a and the high shift 24b are negative and positive shifts as depicted

(not necessarily of the same magnitude). The data signal 22 may multiplex between a low shift 24a and a high shift 24b to provide a data-keyed shift signal 48. A sawtooth waveform generator 46a may be a simple embodiment of a waveform generator 46 designed specifically to operate with the phase modulation device 16b. The modulation waveform 26 provided by the sawtooth waveform generator 46a may be restricted to a sawtooth wave. The sawtooth waveform generator 46 may integrate the total shift signal 44 until reset by a clock signal 49.

As mentioned previously, data keying may significantly affect the structure of the modulation synthesizer 16 specifically and the wavelength shifter 10 generally. In certain embodiments data keying may involve placing a separate phase modulation device 16b in series with the modulation device 16. Other embodiments may involve modifying the modulation device 16 to receive a data keying signal separate from the (wavelength shifting and stabilizing) modulation waveform 26. In many embodiments, however, information to control data keying, wavelength shifting, and wavelength stabilization may be embedded in the modulation waveform 26.

Referring to Figure 8 specifically, while referring generally to all the Figures, the wavelength error detector 14 may include a filter apparatus 50. In one embodiment the filter 50 may include a pair of matched filters 51a and 51b that are slightly offset in wavelength. The wavelength error detector 14 controls the stabilization performed by the wavelength shifter 10 and in certain embodiments may dramatically influence the effectiveness of the wavelength shifter 10.

A differential detector 52 may detect differences of intensity in the output of filter devices 51a and 51b. Figure 8 depicts a pair of filter devices 51a and 51b, which may be fixed. Fixed

filter devices may be sufficient in some applications and may be Bragg filters. In some embodiments, tunable Bragg filters with slightly offset tuning inputs may increase the variety of wavelength patterns supportable with the wavelength error detector 14.

Referring to Figure 9, a tunable version of the wavelength error detector 14 may be comprised of a complementary pair of modulation devices 16a and 16b configured to wavelength shift the channelized photonic signal 20 as directed by the modulation synthesizer 12. In one embodiment, the shift signal 24 carries a wavelength pattern corresponding to a wavelength pattern present on the channelized photonic signal 20.

A complementary pair of modulation devices 16a and 16b may be driven to wavelength shift by a common value corresponding to a wavelength pattern carried by the shift signal 24. Additionally, a slight wavelength offset may be produced between a shifted photonic signal 54a and a shifted photonic signal 54b. Wavelength shifting the channelized photonic signal 20 by slightly different amounts allows the use of a single filter device 51 in the filter apparatus 50 instead of the pair of matching filters devices 51a and 51b slightly offset in wavelength. Filter 51 may be a standard Bragg filter.

Referring to Figure 10, another tunable version of the wavelength error detector 14 may include a filter apparatus 50 having a complementary pair of circulators 55a and 55b, and a bidirectional filter 51c. The bidirectional filter 51c may be a standard Bragg filter. The complementary pair of circulators 55a, 55b may direct the shifted photonic signal 54a and the shifted photonic signal 54b to opposite ends of the bidirectional filter device 51c. The complementary pair of circulators 55a and 55b may also direct the reflected portion of the shifted

photonic signal 54a and the reflected portion of the shifted photonic signal 54b to the differential detector 52.

The tunable versions of the wavelength error detector 14 depicted in Figures 9 and 10 may be designed to create a time-varying wavelength reference using a standard fixed filter device such as a Bragg filter. For example, the channelized photonic signal 20 received by the wavelength error detector 14 may have a wavelength pattern characterized by a spreading function. The complementary pair of modulation devices 16a, 16b may be driven by a modulation waveform characterized by a gathering function corresponding to the spreading function of the channelized photonic signal 20. By using a gathering function that essentially “unspreads” the spreading function, the shifted photonic signals 54a, 54b may be substantially fixed in wavelength. Having substantially fixed wavelengths for the shifted photonic signals 54a, 54b may facilitate using a standard fixed filter device such as a Bragg filter in the wavelength error detector 10.

Some wavelength variability between filter devices may be expected. Additionally, filter device wavelengths are often temperature sensitive. In certain embodiments, temperature- and device-dependent variations between standard filter devices 51 may be compensated. One method of compensation is further adjusting the value of the shift signal 24 of the modulation synthesizer 12 to account for temperature- and device-dependent variations. Thus a modulation synthesizer 12 becomes a temperature-dependent-device-compensation mechanism. A temperature-dependent- device-compensation shift may be stored and accessed externally or internally to the modulation synthesizer 12.



In some embodiments, a tunable version of the wavelength error detector may be shared among multiple wavelength shifters 10. For example, the channelized photonic signals 20 from multiple wavelength shifters 10 may be combined onto a single fiber. On that fiber, a single wavelength error detector 14 may be configured to time-division multiplex between the various channels and provide a time-division-multiplexed wavelength error signal. Additionally, the modulation synthesizer 12 may be configured to sample and hold the wavelength error signal 21 at an appropriate time.

The wavelength shifter 10 provides a convenient building block for creating photonic systems including transmission, switching and multiplexing equipment. Photonic data streams and/or photonic carriers arriving in a photonic signal 18 may be shifted, stabilized and channelized to become the channelized photonic signal 20. This may be done without conversion to the electronic domain. Photonic data rates and throughput may be maintained, while complex control features may be handled in the electronic domain.

Another feature of the wavelength shifter 10 is the ability to transparently pass the photonic signal 18 without knowledge of the encoding techniques or format used to create the photonic signal 18. The transparent nature of the wavelength shifter 10 and the ability to channelize photonic signals facilitates the transmission, multiplexing and switching of an extremely wide range of photonic signals.

The wavelength shifter 10 may also compensate for wavelength variability of existing photonic streams without retransmission. Data may be pre-encoded into the photonic signal 18, or data may be encoded onto the channelized photonic signal 20. Encoding may occur via the shift signal 24 or the optional data signal 22.

Referring to Figure 11, a channel allocation mechanism may automatically channelize and transparently transmit data-encoded photonic streams across a network of photonic equipment without prior knowledge of the carrier wavelengths and data encoding techniques. A channel shifter 58 may have a wavelength detector 60 to receive the photonic signal 18, or the channelized photonic signal 20, and provide a wavelength signature 62.

In certain embodiments, the wavelength signature 62 captures the essential wavelength characteristics of each carrier in a composite or non-composite photonic signal. The channel shifter 58 may also include a wavelength shifter 10 configured to receive the photonic signal 18, or the channelized photonic signal 20, as an input and provide the channelized photonic signal 20 as an output. A channel allocator 64 may be configured to receive the wavelength signature 62 and provide a shift signal 24 that directs the photonic signal 18 or the channelized photonic signal 20 into an available channel.

In some embodiments, the channel allocator 64 may be shared by all the channel shifters 58 common to a system. Sharing the channel allocator 64 simplifies resource allocation, relieves contention and resolves update and data synchronization issues. Multiple channel allocators 64 may also coordinate and update through a variety of methods.

One distributed solution involves assigning a local pool of identified channels to each channel allocator. When a channel allocator exhausts the local pool of channels, a message may be sent to other channel allocators requesting borrowing of a channel from their pool. The request may be accommodated, brokered, negotiated, denied or the like. Regardless of the method relied upon, the channel allocator 64 provides a shift signal to the channel shifter 58. The shift

signal shifts the photonic signal 18 or the channelized photonic signal 20 into an available channel.

Referring to Figure 12, a tunable photonic transmitter 70 may include a coherent light source 72 and a wavelength shifter 10. The photonic signal 18 provided by the coherent light source 72 may have a limited coherence length. The photonic signal 18 may have wavelength jitter sufficient to be unacceptable for a particular application. Additionally, the wavelength of the photonic signal 18 may be offset from the desired wavelength.

The tunable photonic transmitter 70 may shift and stabilize the photonic signal 18 via the wavelength shifter 10 and provide the channelized photonic signal 20. The tunable photonic transmitter 70 may also encode the data signal 22 into the channelized photonic signal 20. The channelized photonic signal 20 may be a spread spectrum channel.

An ability to encode, shift and stabilize the photonic signal 18 independent of the coherent light source 72 may provide additional benefits over standard photonic transmitting circuits. The coherent light source 72 need not be tunable, stable or precise. The coherent light source 72 may be physically and electronically separated from the rest of the photonic transmitter 70. A single optical fiber may connect the coherent light source 72 with the wavelength shifter 10. Performance specifications of the channelized photonic signal 20 may be determined primarily by the electronic circuitry of wavelength shifter 10 rather than the photonics of the coherent light source 72.

Referring to Figure 13, a recursive wavelength shifter 74 may include a shifting loop 76 and an output filter 78. The shifting loop 76 may receive the photonic signal 18, having one or more wavelengths, and provide a photonic signal 18 with a spectral pattern 80. The spectral

pattern 80 may have increasing or diminishing spectral tilt. The spacing and number of wavelengths of the spectral pattern 80 may be varied by the shift signal 24.

The shifting loop 76 may include an amplifier 82, a loop filter 84, and the wavelength shifter 10. The gain of the amplifier 82 may compensate for losses in the shifting loop 76 and contribute to the amount of spectral tilt in the spectral pattern 80. The loop filter 84 may shape the spectral pattern 80 with an arbitrary spectral envelope.

Referring to Figure 14 while also referring to Figure 13, some embodiments the shifting loop 76 effectively generate a spectral comb 86. The spacing of the “teeth” of the spectral comb 86 may be controlled by the shift signal 24. In other embodiments the spectral pattern 80 may be repeating and continuous instead of having discrete “teeth.” The shape of the repeating portion of the spectral pattern 80 may be provided by the photonic signal 18.

The output filter 78 may receive a photonic signal with the spectral pattern 80 and provide a spectrally shaped photonic signal 87. As shown in Figure 14, the output filter 78 may select one tooth or region from the spectral pattern 80 and substantially suppress other teeth or regions of the spectral pattern 80. The recursive wavelength shifter 74 may include multiple output filters 78. Each output filter 78 may select a different tooth or region and provide a unique spectrally shaped photonic signal 87.

From the above discussion, it will be appreciated that the present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative, and not restrictive. The scope of the invention is, therefore, indicated by the appended claims, rather

than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

What is claimed and desired to be secured by United States Letters Patent is:

10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
76  
77  
78  
79  
80  
81  
82  
83  
84  
85  
86  
87  
88  
89  
90  
91  
92  
93  
94  
95  
96  
97  
98  
99  
100  
101  
102  
103  
104  
105  
106  
107  
108  
109  
110  
111  
112  
113  
114  
115  
116  
117  
118  
119  
120  
121  
122  
123  
124  
125  
126  
127  
128  
129  
130  
131  
132  
133  
134  
135  
136  
137  
138  
139  
140  
141  
142  
143  
144  
145  
146  
147  
148  
149  
150  
151  
152  
153  
154  
155  
156  
157  
158  
159  
160  
161  
162  
163  
164  
165  
166  
167  
168  
169  
170  
171  
172  
173  
174  
175  
176  
177  
178  
179  
180  
181  
182  
183  
184  
185  
186  
187  
188  
189  
190  
191  
192  
193  
194  
195  
196  
197  
198  
199  
200  
201  
202  
203  
204  
205  
206  
207  
208  
209  
210  
211  
212  
213  
214  
215  
216  
217  
218  
219  
220  
221  
222  
223  
224  
225  
226  
227  
228  
229  
230  
231  
232  
233  
234  
235  
236  
237  
238  
239  
240  
241  
242  
243  
244  
245  
246  
247  
248  
249  
250  
251  
252  
253  
254  
255  
256  
257  
258  
259  
260  
261  
262  
263  
264  
265  
266  
267  
268  
269  
270  
271  
272  
273  
274  
275  
276  
277  
278  
279  
280  
281  
282  
283  
284  
285  
286  
287  
288  
289  
290  
291  
292  
293  
294  
295  
296  
297  
298  
299  
300  
301  
302  
303  
304  
305  
306  
307  
308  
309  
310  
311  
312  
313  
314  
315  
316  
317  
318  
319  
320  
321  
322  
323  
324  
325  
326  
327  
328  
329  
330  
331  
332  
333  
334  
335  
336  
337  
338  
339  
340  
341  
342  
343  
344  
345  
346  
347  
348  
349  
350  
351  
352  
353  
354  
355  
356  
357  
358  
359  
360  
361  
362  
363  
364  
365  
366  
367  
368  
369  
370  
371  
372  
373  
374  
375  
376  
377  
378  
379  
380  
381  
382  
383  
384  
385  
386  
387  
388  
389  
390  
391  
392  
393  
394  
395  
396  
397  
398  
399  
400  
401  
402  
403  
404  
405  
406  
407  
408  
409  
410  
411  
412  
413  
414  
415  
416  
417  
418  
419  
420  
421  
422  
423  
424  
425  
426  
427  
428  
429  
430  
431  
432  
433  
434  
435  
436  
437  
438  
439  
440  
441  
442  
443  
444  
445  
446  
447  
448  
449  
450  
451  
452  
453  
454  
455  
456  
457  
458  
459  
460  
461  
462  
463  
464  
465  
466  
467  
468  
469  
470  
471  
472  
473  
474  
475  
476  
477  
478  
479  
480  
481  
482  
483  
484  
485  
486  
487  
488  
489  
490  
491  
492  
493  
494  
495  
496  
497  
498  
499  
500  
501  
502  
503  
504  
505  
506  
507  
508  
509  
510  
511  
512  
513  
514  
515  
516  
517  
518  
519  
520  
521  
522  
523  
524  
525  
526  
527  
528  
529  
530  
531  
532  
533  
534  
535  
536  
537  
538  
539  
540  
541  
542  
543  
544  
545  
546  
547  
548  
549  
550  
551  
552  
553  
554  
555  
556  
557  
558  
559  
560  
561  
562  
563  
564  
565  
566  
567  
568  
569  
570  
571  
572  
573  
574  
575  
576  
577  
578  
579  
580  
581  
582  
583  
584  
585  
586  
587  
588  
589  
590  
591  
592  
593  
594  
595  
596  
597  
598  
599  
600  
601  
602  
603  
604  
605  
606  
607  
608  
609  
610  
611  
612  
613  
614  
615  
616  
617  
618  
619  
620  
621  
622  
623  
624  
625  
626  
627  
628  
629  
630  
631  
632  
633  
634  
635  
636  
637  
638  
639  
640  
641  
642  
643  
644  
645  
646  
647  
648  
649  
650  
651  
652  
653  
654  
655  
656  
657  
658  
659  
660  
661  
662  
663  
664  
665  
666  
667  
668  
669  
670  
671  
672  
673  
674  
675  
676  
677  
678  
679  
680  
681  
682  
683  
684  
685  
686  
687  
688  
689  
690  
691  
692  
693  
694  
695  
696  
697  
698  
699  
700  
701  
702  
703  
704  
705  
706  
707  
708  
709  
710  
711  
712  
713  
714  
715  
716  
717  
718  
719  
720  
721  
722  
723  
724  
725  
726  
727  
728  
729  
730  
731  
732  
733  
734  
735  
736  
737  
738  
739  
740  
741  
742  
743  
744  
745  
746  
747  
748  
749  
750  
751  
752  
753  
754  
755  
756  
757  
758  
759  
760  
761  
762  
763  
764  
765  
766  
767  
768  
769  
770  
771  
772  
773  
774  
775  
776  
777  
778  
779  
780  
781  
782  
783  
784  
785  
786  
787  
788  
789  
790  
791  
792  
793  
794  
795  
796  
797  
798  
799  
800  
801  
802  
803  
804  
805  
806  
807  
808  
809  
810  
811  
812  
813  
814  
815  
816  
817  
818  
819  
820  
821  
822  
823  
824  
825  
826  
827  
828  
829  
830  
831  
832  
833  
834  
835  
836  
837  
838  
839  
840  
841  
842  
843  
844  
845  
846  
847  
848  
849  
850  
851  
852  
853  
854  
855  
856  
857  
858  
859  
860  
861  
862  
863  
864  
865  
866  
867  
868  
869  
870  
871  
872  
873  
874  
875  
876  
877  
878  
879  
880  
881  
882  
883  
884  
885  
886  
887  
888  
889  
890  
891  
892  
893  
894  
895  
896  
897  
898  
899  
900  
901  
902  
903  
904  
905  
906  
907  
908  
909  
910  
911  
912  
913  
914  
915  
916  
917  
918  
919  
920  
921  
922  
923  
924  
925  
926  
927  
928  
929  
930  
931  
932  
933  
934  
935  
936  
937  
938  
939  
940  
941  
942  
943  
944  
945  
946  
947  
948  
949  
950  
951  
952  
953  
954  
955  
956  
957  
958  
959  
960  
961  
962  
963  
964  
965  
966  
967  
968  
969  
970  
971  
972  
973  
974  
975  
976  
977  
978  
979  
980  
981  
982  
983  
984  
985  
986  
987  
988  
989  
990  
991  
992  
993  
994  
995  
996  
997  
998  
999  
1000  
1001  
1002  
1003  
1004  
1005  
1006  
1007  
1008  
1009  
1010  
1011  
1012  
1013  
1014  
1015  
1016  
1017  
1018  
1019  
1020  
1021  
1022  
1023  
1024  
1025  
1026  
1027  
1028  
1029  
1030  
1031  
1032  
1033  
1034  
1035  
1036  
1037  
1038  
1039  
1040  
1041  
1042  
1043  
1044  
1045  
1046  
1047  
1048  
1049  
1050  
1051  
1052  
1053  
1054  
1055  
1056  
1057  
1058  
1059  
1060  
1061  
1062  
1063  
1064  
1065  
1066  
1067  
1068  
1069  
1070  
1071  
1072  
1073  
1074  
1075  
1076  
1077  
1078  
1079  
1080  
1081  
1082  
1083  
1084  
1085  
1086  
1087  
1088  
1089  
1090  
1091  
1092  
1093  
1094  
1095  
1096  
1097  
1098  
1099  
1100  
1101  
1102  
1103  
1104  
1105  
1106  
1107  
1108  
1109  
1110  
1111  
1112  
1113  
1114  
1115  
1116  
1117  
1118  
1119  
1120  
1121  
1122  
1123  
1124  
1125  
1126  
1127  
1128  
1129  
1130  
1131  
1132  
1133  
1134  
1135  
1136  
1137  
1138  
1139  
1140  
1141  
1142  
1143  
1144  
1145  
1146  
1147  
1148  
1149  
1150  
1151  
1152  
1153  
1154  
1155  
1156  
1157  
1158  
1159  
1160  
1161  
1162  
1163  
1164  
1165  
1166  
1167  
1168  
1169  
1170  
1171  
1172  
1173  
1174  
1175  
1176  
1177  
1178  
1179  
1180  
1181  
1182  
1183  
1184  
1185  
1186  
1187  
1188  
1189  
1190  
1191  
1192  
1193  
1194  
1195  
1196  
1197  
1198  
1199  
1200  
1201  
1202  
1203  
1204  
1205  
1206  
1207  
1208  
1209  
1210  
1211  
1212  
1213  
1214  
1215  
1216  
1217  
1218  
1219  
1220  
1221  
1222  
1223  
1224  
1225  
1226  
1227  
1228  
1229  
1230  
1231  
1232  
1233  
1234  
1235  
1236  
1237  
1238  
1239  
1240  
1241  
1242  
1243  
1244  
1245  
1246  
1247  
1248  
1249  
1250  
1251  
1252  
1253  
1254  
1255  
1256  
1257  
1258  
1259  
1260  
1261  
1262  
1263  
1264  
1265  
1266  
1267  
1268  
1269  
1270  
1271  
1272  
1273  
1274  
1275  
1276  
1277  
1278  
1279  
1280  
1281  
1282  
1283  
1284  
1285  
1286  
1287  
1288  
1289  
1290  
1291  
1292  
1293  
1294  
1295  
1296  
1297  
1298  
1299  
1300  
1301  
1302  
1303  
1304  
1305  
1306  
1307  
1308  
1309  
1310  
1311  
1312  
1313  
1314  
1315  
1316  
1317  
1318  
1319  
1320  
1321  
1322  
1323  
1324  
1325  
1326  
1327  
1328  
1329  
1330  
1331  
1332  
1333  
1334  
1335  
1336  
1337  
1338  
1339  
1340  
1341  
1342  
1343  
1344  
1345  
1346  
1347  
1348  
1349  
1350  
1351  
1352  
1353  
1354  
1355  
1356  
1357  
1358  
1359  
1360  
1361  
1362  
1363  
1364  
1365  
1366  
1367  
1368  
1369  
1370  
1371  
1372  
1373  
1374  
1375  
1376  
1377  
1378  
1379  
1380  
1381  
1382  
1383  
1384  
1385  
1386  
1387  
1388  
1389  
1390  
1391  
1392  
1393  
1394  
1395  
1396  
1397  
1398  
1399  
1400  
1401  
1402  
1403  
1404  
1405  
1406  
1407  
1408  
1409  
1410  
1411  
1412  
1413  
1414  
1415  
1416  
1417  
1418  
1419  
1420  
1421  
1422  
1423  
1424  
1425  
1426  
1427  
1428  
1429  
1430  
1431  
1432  
1433  
1434  
1435  
1436  
1437  
1438  
1439  
1440  
1441  
1442  
1443  
1444  
1445  
1446  
1447  
1448  
1449  
1450  
1451  
1452  
1453  
1454  
1455  
1456  
1457  
1458  
1459  
1460  
1461  
1462  
1463  
1464  
1465  
1466  
1467  
1468  
1469  
1470  
1471  
1472  
1473  
1474  
1475  
1476  
1477  
1478  
1479  
1480  
1481  
1482  
1483  
1484  
1485  
1486  
1487  
1488  
1489  
1490  
1491  
1492  
1493  
1494  
1495  
1496  
1497  
1498  
1499  
1500  
1501  
1502  
1503  
1504  
1505  
1506  
1507  
1508  
1509  
1510  
1511  
1512  
1513  
1514  
1515  
1516  
1517  
1518  
1519  
1520  
1521  
1522  
1523  
1524  
1525  
1526  
1527  
1528  
1529  
1530  
1531  
1532  
1533  
1534  
1535  
1536  
1537  
1538  
1539  
1540  
1541  
1542  
1543  
1544  
1545  
1546  
1547  
1548  
1549  
1550  
1551  
1552  
1553  
1554  
1555  
1556  
1557  
1558  
1559  
1560  
1561  
1562  
1563  
1564  
1565  
1566  
1567  
1568  
1569  
1570  
1571  
1572  
1573  
1574  
1575  
1576  
1577  
1578  
1579  
1580  
1581  
1582  
1583  
1584  
1585  
1586  
1587  
1588  
1589  
1590  
1591  
1592  
1593  
1594  
1595  
1596  
1597  
1598  
1599  
1600  
1601  
1602  
1603  
1604  
1605  
1606  
1607  
1608  
1609  
1610  
1611  
1612  
1613  
1614  
1615  
1616  
1617  
1618  
1619  
1620  
1621  
1622  
1623  
1624  
1625  
1626  
1627  
1628  
1629  
1630  
1631  
1632  
1633  
1634  
1635  
1636  
1637  
1638  
1639  
1640  
1641  
1642  
1643  
1644  
1645  
1646  
1647  
1648  
1649  
1650  
1651  
1652  
1653  
1654  
1655  
1656  
1657  
1658  
1659  
1660  
1661  
1662  
1663  
1664  
1665  
1666  
1667  
1668  
1669  
1670  
1671  
1672  
1673  
1674  
1675  
1676  
1677  
1678  
1679  
1680  
1681  
1682  
1683  
1684  
1685  
1686  
1687  
1688  
1689  
1690  
1691  
1692  
1693  
1694  
1695  
1696  
1697  
1698  
1699  
1700  
1701  
1702  
1703  
1704  
1705  
1706  
1707  
1708  
1709  
1710  
1711  
1712  
1713  
1714  
1715  
1716  
1717  
1718  
1719  
1720  
1721  
1722  
1723  
1724  
1725  
1726  
1727  
1728  
1729  
1730  
1731  
1732  
1733  
1734  
1735  
1736  
1737  
1738  
1739  
1740  
1741  
1742  
1743  
1744  
1745  
1746  
1747  
1748  
1749  
1750  
1751  
1752  
1753  
1754  
1755  
1756  
1757  
1758  
1759  
1760  
1761  
1762  
1763  
1764  
1765  
1766  
1767  
1768  
1769  
1770  
1771  
1772  
1773  
1774  
1775  
1776  
1777  
1778  
1779  
1780  
1781  
1782  
1783  
1784  
1785  
1786  
1787  
1788  
1789  
1790  
1791  
1792  
1793  
1794  
1795  
1796  
1797  
1798  
1799  
1800  
1801  
1802  
1803  
1804  
1805  
1806  
1807  
1808  
1809  
1810  
1811  
1812  
1813  
1814  
1815  
1816  
1817  
1818  
1819  
1820  
1821  
1822  
1823  
1824  
1825  
1826  
1827  
1828  
1829  
1830  
1831  
1832  
1833  
1834  
1835  
1836  
1837  
1838  
1839  
1840  
1841  
1842  
1843  
1844  
1845  
1846  
1847  
1848  
1849  
1850  
1851  
1852  
1853  
1854  
1855  
1856  
1857  
1858  
1859  
1860  
1861  
1862  
1863  
1864  
1865  
1866  
1867  
1868  
1869  
1870  
1871  
1872  
1873  
1874  
1875  
1876  
1877  
1878  
1879  
1880  
1881  
1882  
1883  
1884  
1885  
1886  
1887  
1888  
1889  
1890  
1891  
1892  
1893  
1894  
1895  
1896  
1897  
1898  
1899  
1900  
1901  
1902  
1903  
1904  
1905  
1906  
1907  
1908  
1909  
1910  
1911  
1912  
1913  
1914  
1915  
1916  
1917  
1918  
1919  
1920  
1921  
1922  
1923  
1924  
1925  
1926  
1927  
1928  
1929  
1930  
1931  
1932  
1933  
1934  
1935  
1936  
1937  
1938  
1939  
1940  
1941  
1942  
1943  
1944  
1945  
1946  
1947  
1948  
1949  
1950  
1951  
1952  
1953  
1954  
1955  
1956  
1957  
1958  
1959  
1960  
1961  
1962  
1963  
1964  
1965  
1966  
1967  
1968  
1969  
1970  
1971  
1972  
1973  
1974  
1975  
1976  
1977  
1978  
1979  
1980  
1981  
1982  
1983  
1984  
1985  
1986  
1987  
1988  
1989  
1990  
1991  
1992  
1993  
1994  
1995  
1996  
1997  
1998  
1999  
2000  
2001  
2002  
2003  
2004  
2005  
2006  
2007  
2008  
2009  
2010  
2011  
2012  
2013  
2014  
2015  
2016  
2017  
2018  
2019  
2020  
2021  
2022  
2023  
2024  
2025  
2026  
2027  
2028  
2029  
2030  
2031  
2032  
2033  
2034  
2035  
2036  
2037  
2038  
2039  
2040  
2041  
2042  
2043  
2044  
2045  
2046  
2047  
2048  
2049  
2050  
2051  
2052  
2053  
2054  
2055  
2056  
2057  
2058  
2059  
2060  
2061  
2062  
2063  
2064  
2065  
2066  
2067  
2068  
2069  
2070  
2071  
2072  
2073  
2074  
2075  
2076  
2077  
2078  
2079  
2080  
2081  
2082  
2083  
2084  
2085  
2086  
2087  
2088  
2089  
2090  
2091  
2092  
2093  
2094  
2095  
2096  
2097  
2098  
2099  
2100  
2101  
2102  
2103  
2104  
2105  
2106  
2107  
2108  
2109  
2110  
2111  
2112  
2113  
2114  
2115  
2116  
2117  
2118  
2119  
2120  
2121  
2122  
2123  
2124  
2125  
2126  
2127  
2128  
2129  
2130  
2131  
2132  
2133  
2134  
2135  
2136  
2137  
2138  
2139  
2140  
2141  
2142  
2143  
2144  
2145  
2146  
2147  
2148  
2149  
2150  
2151  
2152  
2153  
2154  
2155  
2156  
2157  
2158  
2159  
2160  
2161  
2162  
2163  
2164  
2165  
2166  
2167  
2168  
2169  
2170  
2171  
2172  
2173  
2174  
2175  
2176  
2177  
2178  
2179  
2180  
2181  
2182  
2183  
2184  
2185  
2186  
2187  
2188  
2189  
2190  
2191  
2192  
2193  
2194  
2195  
2196  
2197  
2198  
2199  
2200  
2201  
2202  
2203  
2204  
2205  
2206  
2207  
2208  
2209  
2210  
2211  
2212  
2213  
2214  
2215  
2216  
2217  
2218  
2219  
2220  
2221  
2222  
2223  
2224  
2225